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SYNOPSIS Wave transmission tests were conducted on specimens of Eglin and Ottawa 20-30 sands at saturations varying from dry to near 100% using a Split-Hopkinson Pressure Bar. Specimens were compacted to a constant dry density in a thick-walled stainless steel container using a standard Proctor hammer. Compacted specimens were loaded in undrained, dynamic uniaxial confined compression at strain rates of approximately 13/s to 19/s. Tests were conducted on dry specimens; specimens compacted moist and tested moist; specimens compacted moist and dried before testing. For a constant input stress, transmitted stress and compressional wave propagation velocity were seen to vary with saturation. The experimental evidence suggests that the observed behavior can be attributed to variations in soil stiffness, microstructure and locked-in stresses as a result of moisture conditions present during compaction.

INTRODUCTION

The prediction of ground motions from explosive detonations and their effects on structures requires information about the response of geologic materials to intense transient loadings. Current methods generally use material properties data based on conventional weapons detonations in dry, or to a limited extent, saturated soils. However, most soils whether natural deposits or placed as engineered fills, are usually at some saturation between 0% and 100%. In addition, engineering analyses typically assume little or no material property changes occur under dynamic loadings, and do not account for the effects of moisture on energy transmission in soils.

Since soil in general is a multiphase media consisting of solids, water and air, its dynamic and static behavior are both very complex. Stress wave propagation in particulate media such as soils depends on a number of parameters including effective stress, density, moisture, stiffness, stress history, applied stress intensity, soil microstructure, and the nature of the material itself. However, the interrelationships among these factors in determining soil behavior are not fully understood and there are currently no theoretical, empirical or numerical methods available for predicting large amplitude compressive stress wave velocity and stress transmission in unsaturated soils (3,10,154). This is primarily due to an incomplete understanding of load transfer mechanisms in soils under transient dynamic loadings, particularly moist soils.

This paper describes experimental research to investigate the dynamic undrained uniaxial compressive stress transmission behavior of compacted moist soils using a Split-Hopkinson Pressure Bar at AFCESA/RACS, Tyndall AFB, FL. The SHPB has been successfully used with concrete, metals, composites and foams at high strain rates. Special equipment and techniques were developed for using the SHPB with soils.

BACKGROUND

Recent research (1,2,9-13) using the Tyndall SHPB to study unsaturated soil behavior has shown that: a) the presence/amount of moisture significantly affects the dynamic and static response; and b) the transmitted stress, wave speed and stiffness vary with the amount of moisture present during compaction. Also, the influence of capillary pressures on the stiffness of sands has been shown to be negligible (≤ about 7 kPa) compared with high intensity transient dynamic loadings. However, the results, including those of this investigation, suggest that capillary pressures may strongly influence the soil microstructure, particle orientations and locked-in stresses developed during compaction which could significantly affect the dynamic and static soil behavior.

Studies by a number of other investigators have also shown that the compaction of sands with moisture present has a measurable influence on dynamic and static soil properties which can be attributed to variations in soil stiffness and microstructure. Dynamic SHPB uniaxial compression tests of soils (4,13), and also quasi-static tests (1,2,12) have shown a saturation dependent stress-strain behavior. The effects of sand fabric and sample preparation method on liquefaction behavior of sands were studied by (7) who observed significant differences in cyclic triaxial behavior based on how specimens were prepared. In a study of 11 different packing methods, it was demonstrated that the compaction method and initial moisture conditions, strongly influence the cyclic liquefaction behavior of fine sands (8). Resonant column tests of fine sands showed that capillary pressures in specimens compacted moist at saturations in the range of from 5% to 20% produced a significant increase in the dynamic shearing modulus (15).

Sandstone rock cores have also been studied to investigate the effects of saturation and confining pressure on compressional wave velocity (5). Results indicated that wave velocity increased between 0% and about 20% saturation, remained constant between about 20% and 90% saturation, decreasing thereafter for confining pressures between 105 and 526 kPa. At higher pressures, the wave speed was constant up to about 90% saturation. These results are remarkably similar to those obtained by (1,2,9-13) and presented in this paper for SHPB tests of uncemented sands compacted at different saturations.

While these various effects on soil behavior have been observed experimentally by a number of researchers, a clear, concise explanation of the phenomenon is not currently available. This is primarily due to the fact that the multiphase behavior of unsaturated soils, the interaction between the individual phases (air, water and solid), and load transfer mechanisms in soils are not well understood.

EXPERIMENTAL INVESTIGATION

Materials Tested and Specimen Preparation

Two different granular soils were tested using the SHPB at Tyndall AFB: Eglin sand (from Eglin AFB) and Ottawa 20-30 sand (commercially available). Eglin sand is medium to fine, angular to subangular with about 7% fines; Ottawa 20-30 sand is medium, uniformly graded, subrounded to rounded with no fines. Table 1 gives physical properties data and Fig. 1 compares the grain size distributions.

Specimens of each sand were compacted to a constant dry density (1,715 kg/m^3 for Ottawa 20-30 sand and 1,755 kg/m^3 for Eglin sand) at saturations varying from 0% to 100% using a Standard Proctor hammer. Four individual layers of equal mass were compacted to 2.54 cm in length for a final total specimen length of 10.16 cm at a constant dry density for each soil. All specimens were prepared in a 7.62 cm long seamless stainless steel container with 2.54 cm thick wall and 5.08 cm inside diameter. The rigid thick-walled container was used during SHPB testing to simulate the one-dimensional strain conditions typically encountered near explosive detonations.

For moist specimens, the amount of water for a given saturation at final compacted density was thoroughly mixed with dry soil and allowed to equilibrate before compaction. For dry specimens, soil was poured directly into the specimen container and compacted. The required compactive effort to obtain a constant dry density for each soil varied with the amount of moisture. Compacted specimens were held in place by two 0.635 cm thick stainless steel wafers fitted with o-ring seals to prevent pore fluid drainage at the base during specimen preparation and SHPB testing (Fig. 2). One wafer was inserted prior to compaction and the other carefully placed after compaction to ensure full contact with the specimen.

Split-Hopkinson Pressure Bar (SHPB)

The Tyndall SHPB facility consists of: a) a dynamic loading system with a nitrogen pressurized cannon to fire 5.08 cm diameter stainless steel projectiles (striker) of varying lengths at the incident bar; b) a 5.08 cm diameter, 3.66 m long stainless steel incident bar; c) a 5.08 cm diameter, 3.35 m long stainless steel transmitter bar; d) electronic strain gage instrumentation; e) a digital storage oscilloscope; and f) a desktop computer for data analysis. The SHPB facility is shown schematically in Fig. 3. A brief overview of the SHPB is given here and details of system, principles of operation, and theory are given by (6,9,10).

The SHPB system loads a specimen with a one-dimensional transient compressive stress wave at normal incidence by impacting a steel bar on one side of a specimen (incident bar) with a projectile (striker). An identical steel bar on the other side of the specimen (transmitter bar) captures the stress wave transmitted by the specimen. During testing, measurements of incident, reflected and transmitted strains

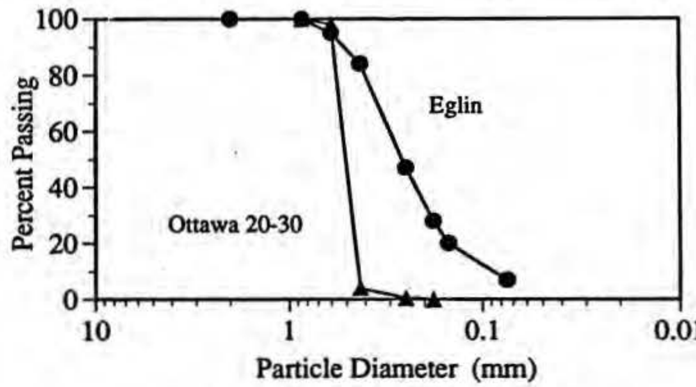

Fig. 1 Grain Size Distributions.

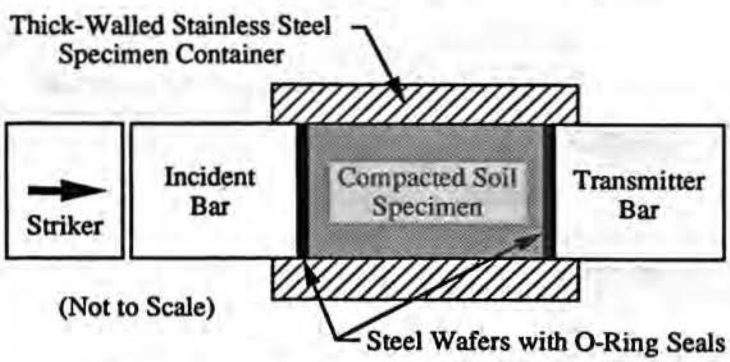

Fig. 2. Compacted Soil Specimen in the SHPB Device.

Table 1. Physical Properties Data for Sands Tested.

	Eglin	Ottawa 20-30
USCS Classification	SP-SM	SP
Specific Gravity	2.65	2.65
D_{50} (mm)	0.26	0.70
C_u	3.41	1.40
C_c	1.29	1.03
% -#100	12	<1
% -#200	7	0
$(\gamma_d)_{max}$ (kg/m^3)	1,755	1,715
$(\gamma_d)_{min}$ (kg/m^3)	1,450	1,560
Max.void ratio	0.817	0.705
Min. void ratio	0.510	0.545
Tested γ_d (kg/m^3)	1,755	1,715

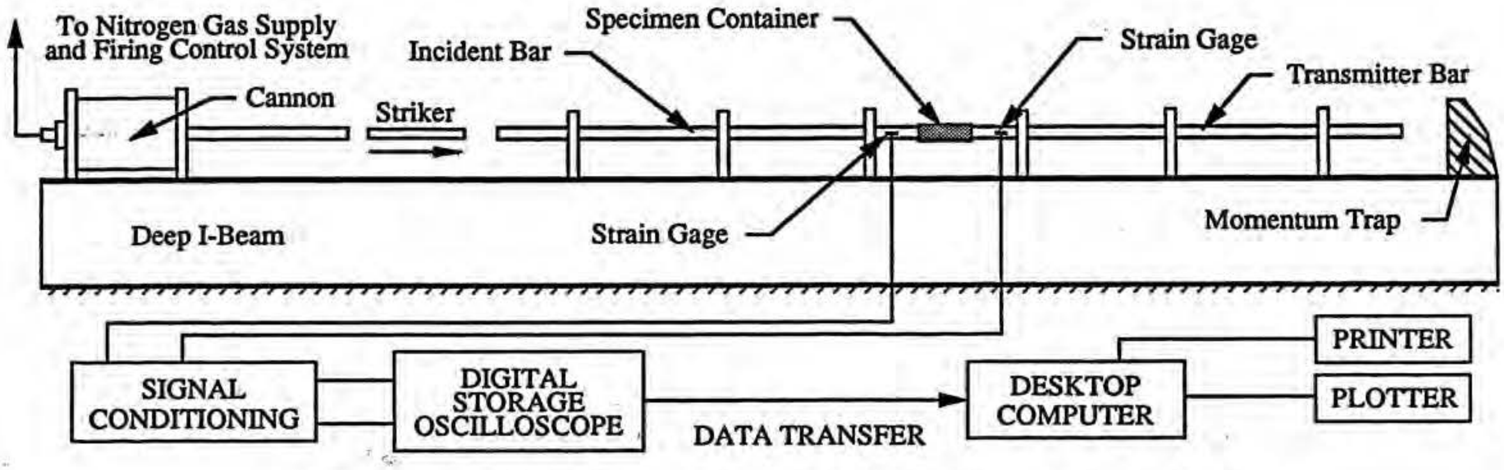

Fig. 3. Overview of Split-Hopkinson Pressure Bar Test Facility at Tyndall AFB.

in the bars are made by the strain gages. Transmitted energy and wave speed are determined by analyzing the transient strain gage measurements. In wave propagation tests, a striker length is chosen such that the pulse length is shorter than the transit time across the specimen length. In this research, a pulse length of about 80 μs was used which is less than the 250 μs to 150 μs transit time range for the 10.16 cm long soil specimens (assuming a wave speed of 400 m/s to 700 m/s). The shorter loading pulse allows the transmitter bar strain gage to record the first arrival of the compressive stress wave before multiple reflections begin.

The strain gage data are used to determine the magnitude of the incident and transmitted elastic stresses in the bars. The transmission ratio, TR, can be used as a measure of the amount of stress transmitted through the specimen (TR=1.0 for bars in full contact without a specimen). From elastic theory (6) it can be shown that the TR can be written in terms of the stress measured at the transmitter bar, σ_t' , the stress measured at the incident bar, σ_i , and the material properties of the bars and the specimen between them:

$$TR = \frac{(\sigma_t')}{(\sigma_i)} = \frac{(4)[(\rho V_c)_{bar}(\rho V_c)_{soil}]}{[(\rho V_c)_{bar} + (\rho V_c)_{soil}]^2} \qquad (1)$$

where ρ is the mass density (total mass density for soil) and V_c is the compressive stress wave propagation velocity. Eq. (1) assumes: a) the incident and transmitter bars are of the same material (same ρ and V_c); b) both bars and the specimen have the same cross-sectional area; c) both bars and specimen are prismatic; d) the bars are loaded in the elastic range; and e) normal incidence of the applied stress.

The compressional wave propagation velocity through the specimen, V_c , is determined from the strain-time data recorded by the strain gages using:

$$V_c = \frac{\left[(t_o)_t - (t_o)_i\right] - t_{bars}}{L_o} \qquad (2)$$

where $(t_o)_t$ and $(t_o)_i$ are the times at the leading edge of the transmitter and incident bar stress waves, respectively, t_{bars} is the transit time through the bars between the strain gages, and L_o is the initial specimen length. Typical strain gage output data are shown in Fig. 4.

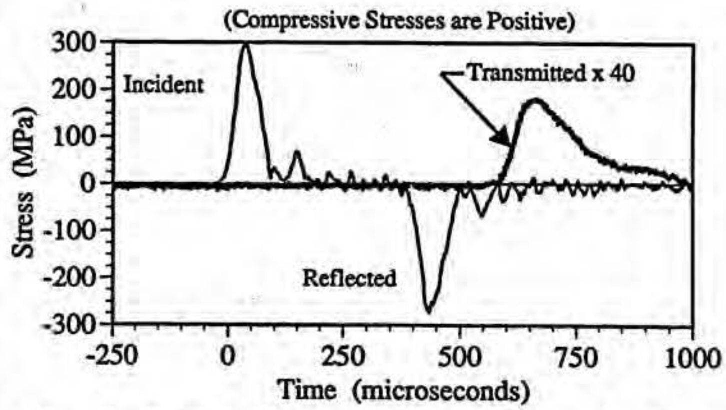

Fig. 4. Typical SHPB Strain Gage Data for Wave Propagation Tests of Soils.

RESULTS and DISCUSSION

Compaction Energy

During sample preparation, the number of Standard Proctor hammer blows to obtain the required dry density at each saturation for each specimen was recorded. Fig. 5 compares the compactive energy as a function of saturation and soil type. Curves through the data indicate average values. The results show a measurable dependency of compactive energy on moisture for a constant dry density packing which is particularly strong for the Ottawa 20-30 sand. The general trends in the data indicate that the required compactive energy increases from 0% to about 20% saturation, remains constant from about 20% to 50% saturation, and decreases thereafter. The Eglin sand typically required less compactive effort as moisture was added compared to the Ottawa 20-30 sand which is most likely due to its wider range of particle sizes including fines.

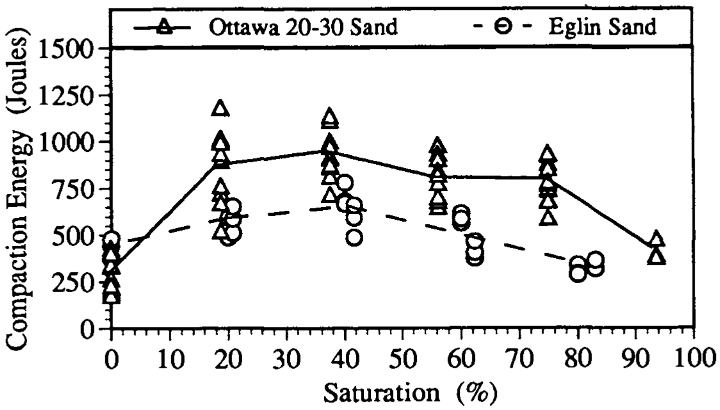

Fig. 5. Comparison of Required Compaction Energy.

Split-Hopkinson Pressure Bar Tests

Dynamic, undrained uniaxial confined compression SHPB tests were conducted on the Eglin, and Ottawa 20-30 sands at saturations varying from 0% to 94% and a constant dry density. A 20.32 cm long striker was fired at a velocity of about 1,305 cm/s, producing a triangular input stress of approximately 290 MPa, peak stress rise time of about 50 μs, an 80 μs pulse width, and strain rates of 13/s to 19/s.

Two series of SHPB tests were conducted on the Eglin and Ottawa 20-30 sands to study stress transmission and compressional wave speed as a function of saturation. The first series ("moist/moist") involved compacting specimens moist and then testing them immediately to provide information about the effects of moisture during compaction and testing on the dynamic soil response. The second series ("moist/dry") was conducted on specimens compacted moist, oven-dried, and then tested in the SHPB. These additional tests were used to determine if the conditions developed during compaction remained locked-in the soil structure even after the moisture had been removed from the pores. Specimens were handled carefully to preserve the structure and preferred particle orientations formed during compaction prior to SHPB testing.

Tables 2 and 3 summarize the various data for the Eglin and Ottawa 20-30 sands, respectively. Figs. 6 to 9 show test data for TR and V_C normalized to the average dry values for each soil as a function of saturation. Curves through the data indicate average values. The saturations shown in the tables and figures represent the moisture conditions during compaction/testing for the moist/moist (tested moist) series and during compaction for the moist/dry series (tested dry).

Fig. 6 shows the normalized TR data for Eglin sand. The moist/moist data show an increase in TR from 0% to about 20% saturation, remaining constant to about 60% saturation, decreasing thereafter to about 80% saturation. The moist/dry data show a significantly larger increase in TR from 0% to about 40% saturation, decreasing below the moist/moist data beyond about 50% saturation. The TR nearly doubled for the moist/dry tests and increased by as much as a factor of 3.5 for the moist/dry tests compared with that for dry soil.

Table 2. SHPB Data for Eglin Sand.

S (%)	[a]TR	[a]V_C (m/sec)	[b]TR	[b]V_C (m/sec)
0	0.022	465	---	---
0	0.017	422	---	---
0	0.016	455	---	---
0	0.016	458	---	---
0	0.016	465	---	---
0	0.018	456	---	---
20	---	---	0.059	703
20	---	---	0.059	680
20	---	---	0.074	658
20.8	0.033	564	---	---
20.8	0.037	569	---	---
20.8	0.037	578	---	---
20.8	0.032	562	---	---
20.8	0.037	559	---	---
20.8	0.048	555	---	---
40	---	---	0.047	536
40	---	---	0.065	576
40	---	---	0.059	536
41.6	0.036	561	---	---
41.6	0.041	561	---	---
41.6	0.035	565	---	---
41.6	0.038	565	---	---
41.6	0.028	522	---	---
60	---	---	0.011	413
60	---	---	0.014	404
60	---	---	0.022	440
62.4	0.035	533	---	---
62.4	0.044	587	---	---
62.4	0.039	574	---	---
62.4	0.035	533	---	---
62.4	0.030	522	---	---
62.4	0.034	552	---	---
80	---	---	0.007	289
80	---	---	0.006	284
80	---	---	0.009	355
83.1	0.006	289	---	---
83.1	0.019	489	---	---
83.1	0.006	292	---	---
83.1	0.006	287	---	---
83.1	0.019	463	---	---
83.1	0.018	327	---	---

Note: a Compacted moist and tested moist (for S>0%).
b Compacted moist and tested dry.

Fig. 7 shows the normalized TR data for Ottawa 20-30 sand. The moist/moist data show an increase in TR from 0% to about 40% saturation, followed by a gradual decrease to about 75% saturation. The moist/dry data show an increase in TR from 0% to about 20% saturation, followed by a gradual decrease to about 75% saturation. Compared with dry soil, the largest TR increase was to about 1.5 for the moist/dry tests and to about 1.25 for the moist/dry tests compared with that for dry soil.

Fig. 8 shows the normalized V_C data for Eglin sand. The moist/moist data show an increase in V_C from 0% to about 20% saturation, remaining constant to about 60% saturation,

Table 3. SHPB Data for Ottawa 20-30 Sand.

S (%)	[a]TR	[a]V_c (m/sec)	[b]TR	[b]V_c (m/sec)
0	0.026	364	---	---
0	0.030	479	---	---
0	0.020	391	---	---
0	0.051	552	---	---
0	0.052	536	---	---
0	0.033	495	---	---
0	0.027	497	---	---
0	0.043	600	---	---
0	0.067	635	---	---
0	0.046	571	---	---
0	0.075	618	---	---
18.7	0.035	603	0.058	610
18.7	0.043	491	0.058	643
18.7	0.064	612	0.074	637
18.7	0.053	565	---	---
37.4	0.065	581	0.054	520
37.4	0.073	600	0.078	654
37.4	0.042	554	0.052	579
56.2	0.039	535	0.048	478
56.2	0.046	586	0.049	513
56.2	0.066	565	0.061	643
56.2	---	---	0.076	607
74.9	---	---	0.020	456
74.9	0.014	325	0.073	612
74.9	0.036	555	0.061	576
74.9	0.052	571	0.068	582
93.6	0.031	571	---	---
93.6	0.042	527	---	---
93.6	0.031	546	---	---

Note: a Compaced moist and tested moist (for S>0%).
b Compaced moist and tested dry.

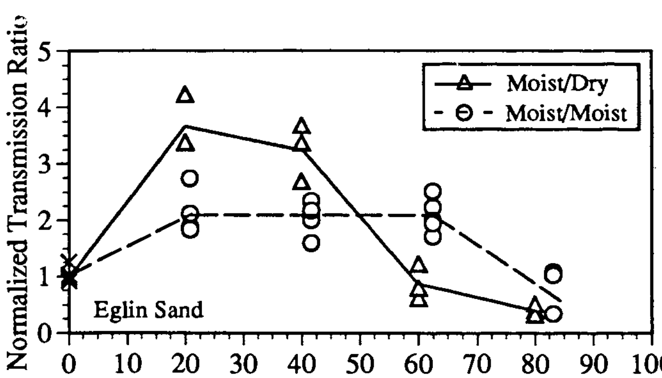

Fig. 6. Normalized Transmission Ratio for Eglin Sand.

and decreasing thereafter to about 80% saturation which is similar to that of the TR data. The moist/dry data show a somewhat larger increase in V_c from 0% saturation to about 20% saturation then a steady decrease to 80% saturation which goes below the moist/moist data starting at about 40% saturation. The largest increase in V_c was to about 1.2 for the moist/dry tests and to about 1.5 for the moist/dry tests compared with that for dry soil. The general trends are similar to those shown in Fig. 6 for the TR data.

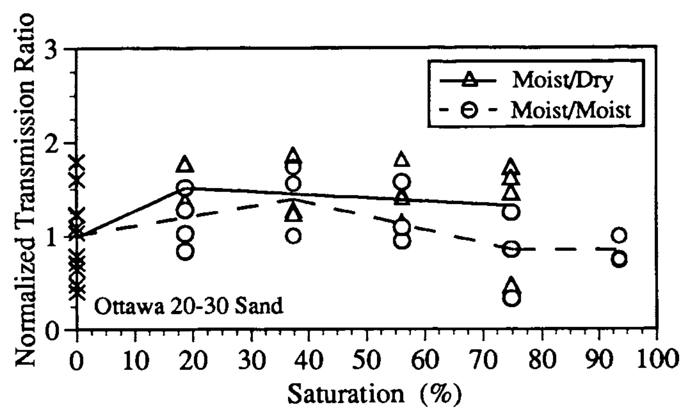

Fig. 7. Normalized Transmission Ratio for Ottawa 20-30 Sand.

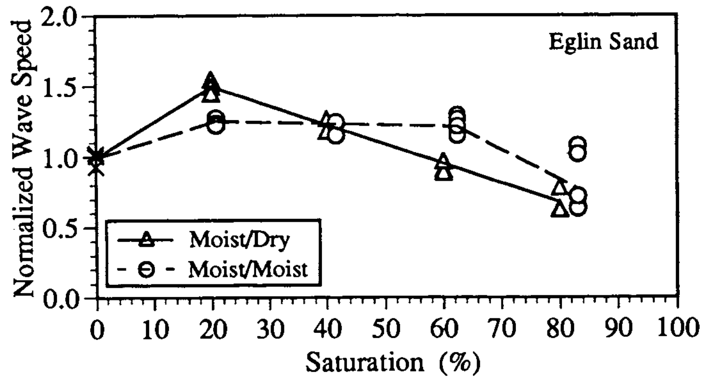

Fig. 8. Normalized Wave Speed for Eglin Sand.

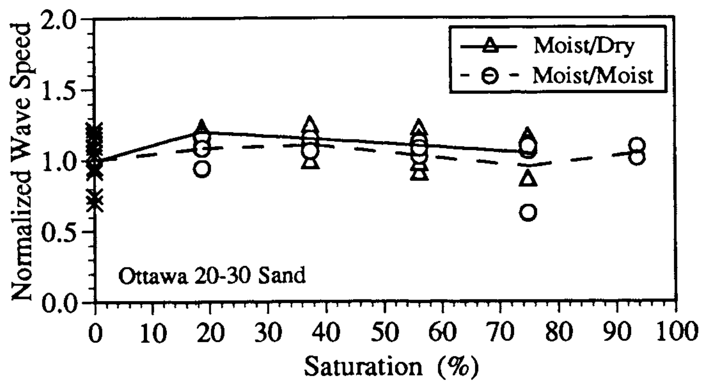

Fig. 9. Normalized Wave Speed for Ottawa 20-30 Sand.

Fig. 9 shows the normalized V_c data for Ottawa 20-30 sand. The moist/moist and moist/dry data show nearly identical trends in V_c variation with saturation, with a small increase from 0% to about 20% saturation, gradually decreasing thereafter to about 75% saturation. The moist/moist data show an increase from about 75% to 90% saturation which is expected since the saturated soil/water mixture should approach the compressional wave speed of water as the saturation nears 100%. Compared with dry soil, the largest increase in was on the order of about 1.25 times that for dry soil. There is not a significant difference between the moist/moist and moist/dry data. The general trends are similar to those shown in Fig. 8 for the TR data.

Relative increases in TR for Eglin sand are much larger than those for Ottawa 20-30 sand compared with data for dry soil. The Eglin sand V_C data also show more sensitivity to changes in saturation than the Ottawa 20-30 sand and there are some significant differences between the moist/moist and moist/dry test conditions. For all practical purposes, there is little difference for the Ottawa 20-30 data whether tested moist/moist or moist/dry.

CONCLUSIONS

- SHPB test results indicate that the amount of moisture present during compaction significantly influences the dynamic behavior of Eglin and Ottawa 20-30 sands. The data suggest that moisture affects soil stiffness, microstructure, preferred particle orientations and the development of locked-in stresses. Eglin sand generally showed greater sensitivity to changes in saturation for both the transmission ratio and compressional wave speed data than did Ottawa 20-30 sand.

- Moist/dry SHPB test results indicate that conditions in the soil specimens developed during compaction remained intact even after the moisture in the pores has been removed by drying. This testing condition had the most significant effects on the Eglin sand dynamic behavior.

- The compactive energy required to obtain a constant dry density specimen is strongly dependent on the amount of moisture present, more so for the Ottawa 20-30 sand than the Eglin sand. Generally, the largest amount of compactive effort was needed at about 20-50% saturation, while the least amount was for dry packing.

- This investigation represents an important step towards developing a fundamental understanding of the dynamic and static behavior of unsaturated soils and how they transmit applied forces. Results of such studies have direct applications to groundshock prediction techniques including stress transmission to structures.

(The authors have also conducted microstructural analyses of compacted dry and moist Ottawa 20-30 sand specimens which will be the subject of a future journal publication.)

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